NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-788

Irradiate-Anneal Screening of Total Dose Effects in Semiconductor Devices

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CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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PREFACE

The work described in this report was performed by the Astrionics Division of the Jet Propulsion Laboratory.

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Abstract

An extensive investigation of irradiate-anneal (IRAN) screening against total dose radiation effects was carried out as part of a program to harden the Mariner Jupiter/Saturn 1977 (MJS'77) spacecraft to survive the Jupiter radiation belts (Ref. 1). The method consists of irradiating semiconductor devices with Cobalt-60 to a suitable total dose under representative bias conditions and of separating the parts in the undesired tail of the distribution from the bulk of the parts by means of a predetermined acceptance limit. The acceptable devices are then restored close to their preirradiation condition by annealing them at an elevated temperature. IRAN was used when lot screen methods were impracticable due to lack of time, and when members of a lot showed a diversity of radiation response.

The feasibility of the technique was determined by IRAN testing performed on a number of types of linear bipolar integrated circuits, analog switches, n-channel JFETs and bipolar transistors. Total doses from 50 to 150 krad(Si) were used for screening. The devices were annealed at $150^{\circ}C$ for 96 hours, followed by reirradiation to 4 radiation levels from 5×10^{11} to 5×10^{12} e/cm^2.

The parametric changes produced in each linear bipolar device by equal doses of the first and second irradiation were plotted to show the ratio of the shift produced as well as any anomalous data points. It was found that each device had its own peculiar response. However, some general conclusions could be drawn. In almost all cases reirradiation produces substantially greater shifts than the original radiation. On annealing, most parameters recover to within the manufacturer's specification limits, except open loop gain and input bias current of some device types. It was found that in most linear bipolar devices the electrical parameter response to the initial radiation exposure exhibited slow changes up to about 35 krad(Si) followed by a logarithmic change of the type: $P = k\log\Phi + C$. The response on reirradiation becomes logarithmic at about 10 krad(Si) and of the type: $P = k\log(\Phi - \Phi_0) + C$. However there were many anomalous curves for specific device types, particularly for the input offset current. The majority of the anomalies are predictable by deviant values after the first irradiation and anneal. These may be eliminated by suitable acceptance criteria specific to each parameter of each device type.

N-channel JFETs exposed with 10 to 20 V gate bias showed an increase of I_{GSS} of at least one order of magnitude, with even greater increases when inversion layers were produced. Above 60 krad(Si), $I_{GSS} = (K\Phi)^a$ with a varying between 2 and 5. Analog switches showed a similar behavior, but without the induced inversion layer and with correspondingly lower values of a.

Based on the results of these experiments a number of device types were selected for IRAN of flight parts in the MJS'77 spacecraft systems. The part types, screening doses, acceptance criteria, number of parts tested and rejected as well as the program steps are detailed.

I. INTRODUCTION

An extensive investigation of irradiate-anneal screening of semiconductor piece parts against total dose radiation effects was carried out as part of a program to harden the Mariner Jupiter/Saturn (MJS'77) spacecraft against the Jupiter radiation belts (Ref. 1). The method consists of irradiating semiconductor devices with Cobalt-60 to a suitable total dose under representative bias conditions and of separating the undesired tail of the distribution from the bulk of the parts by means of a predetermined acceptance limit. The acceptable devices are then restored to their preirradiation condition by annealing them at an elevated temperature.

Irradiate-anneal (IRAN) is the only known 100 percent radiation screen against "mavericks", i.e., devices that are significantly more sensitive to ionizing radiation than the remaining population. In general, IRAN should be supplemented by a qualification test based on a diffusion-metallization lot, in which a few samples are irradiated to a total dose in excess of the project requirements. Failure to pass this test implies lot rejection resulting in an extension of the parts delivery by many months.

Since the lot screening method imposed intolerable time delays, it was hoped that the irradiate-anneal technique might be employed to predict the radiation behavior of each device in a quantitative manner, so that even lots of marginal radiation quality might be utilized at a somewhat lower yield. This requirement imposes far more severe constraints on the retracking of electrical parameters measured after the first irradiation than the elimination of mavericks.

II. PREVIOUS WORK

The problems encountered in radiation screening semiconductor devices against the ionizing radiation environment found in space are first described in a paper by Holmes-Siedle et al. (Ref. 2). The authors investigated beta loss in bipolar transistors. They discovered that samples of the same transistor type from different manufacturers, and even from different batches of the same manufacturer, showed marked differences in behavior.*

The frequency distribution of the damage factor, $\Delta(1/h_{FE})$, data points for a given batch showed a log-normal distribution, so that a worst-case upper limit of anticipated transistor gain degradation could be defined as the maximum value of $\Delta(1/h_{FE})$, corresponding to three times the standard deviation. There were several instances, however, when one or two transistors from an apparently homogeneous group would degrade much more severely than the rest, particularly at low collector currents. Holmes-Siedle attributed these 'mavericks' to uncontrolled variables in the surface preparation of the transistors. Horne and Folsom (Ref. 4) attempted to treat the 'maverick' problem statistically. They, and other authors referred to in their paper, showed that the degradation of bipolar transistors in an ionizing radiation environment obeys the Weibull distribution, i.e., the fraction, F, of devices that fail a given acceptance criterion relating to beta degradation may be expressed as follows:

$$F = 1 - \exp(-D/\theta)^b$$

where D is the radiation dose, and b and θ are constants known as the Weibull slope and characteristic life respectively. The distribution is not truncated at low readiation levels. In fact 0.1 percent failure probabilities can occur at dose of the order of 10^3 rad(Si). Some of the distributions are bimodal or else indicate the presence of more than one failure mode.

1. Irradiate-Anneal

Holmes-Siedle et al. (Ref. 2) discovered that the beta loss from surface effects could be almost completely restored in most planar transistors by annealing at a temperature of 200°C. On irradiating these transistors a second time, their behavior followed the same general pattern observed during the first irradiation.

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*Arimura et al. (Ref. 3) showed that different wafers from the same diffusion lot varied erratically.

They suggested that this technique could be used in a pre-selection procedure that would both identify and eliminate the unusually radiation sensitive transistors.

In a later paper Poch and Holmes-Siedle (Ref. 5) describe the application of the 'irradiate-anneal' preselection technique to a number of planar bipolar transistors. The devices were irradiated by Cobalt-60 to a total dose of 50 krad(Si) followed by annealing at 250°C for 16 hours. On reirradiation the d.c. gain degraded to within 20 percent of the value obtained after the first irradiation.

Shafer and Burghard (Ref. 6) applied the technique to gain and leakage currents of two bipolar transistor types. The devices were irradiated by Cobalt-60 to a total dose of 100 krad(Si) followed by annealing at 275 or 300°C for 60 hours. They observed a slight improvement in the radiation hardness after each successive reirradiation.

Arimura et al. (Ref. 3) made a thorough investigation of the reliability of the irradiate-anneal technique using one operational amplifier and one sense amplifier as the test vehicle. The first irradiation was carried out on a Cobalt-60 source to the same total dose as that in subsequent irradiations: this was either 2.7×10^5 or 5.6×10^6 rad(Si). The devices were annealed at 300°C for two hours. Some of the devices did not anneal and were even further degraded by this step. On reirradiation 90 to 95 percent of the devices showed retracking of the parameters measured after the first irradiation. The operational amplifiers showed a large increase in the input bias current.

Arimura discovered that two additional criteria need to be applied in order to obtain 100 percent correlation between the results of the first and second irradiation. All devices with erratic annealing behavior must be eliminated from the population under test. In addition the acceptance criteria after the first irradiation must be made considerably more stringent than the criteria applicable after the second irradiation. This increase in the selection reliability is accompanied by a significant loss in yield.

Arimura briefly considered the effect of high temperature annealing, which might damage the devices by impurity diffusion of mobile species. He recommended mean time before failure (MTBF) studies on irradiated devices and thermal stress experiments on unirradiated control devices, but no experimental studies were performed.

2. Low Dose Screening

Poch and Holmes-Siedle (Ref. 5) advocated radiation screening at 100 to 1000 rad(Si). They claimed that this dose is sufficient to detect the mavericks, if the collector current in bipolar transistors is kept below 1 μA. The good devices are so little affected that the annealing step may be omitted. Arimura et al. (Ref. 3) found this method to be unsatisfactory, because there was no correlation between the degradation at low and at high doses, nor was there any correlation between the damage at high and low current densities. This applied both to bipolar transistors and to operational amplifiers.

Singletary and Winslow (Ref. 7) used radiation screening at 60 krad(Si) to predict the behavior of bipolar transistors at 6 Mrad (Si), based on the assumption that $(1/h_{FE})$ is proportional to the logarithm of the total dose. No assessment has been made of the effectiveness of the screen against mavericks.

3. Irradiate-Anneal on Semiconductor Wafers

Cates et al. (Ref. 8) first applied "irradiate-anneal" techniques to semiconductor wafers in the hope of rejecting maverick devices at the wafer stage. They were concerned with neutron radiation only. Pease and Ondrik (Ref. 9) used the same technique on the total dose degradation of bipolar transistors. The wafers were annealed at 300°C for two hours in an inert atmosphere. After annealing the values of h_{FE} were uniformly 10 to 15 percent higher than before irradiation. All mavericks either had an abnormally low value of h_{FE} before irradiation or else they were located at the edge of the wafer.

Arimura et al. (Ref. 3) considered the wafer technique to be unsatisfactory, because repetitive wafer probing can cause mechanical damage, and because some electrical measurements cannot be carried out reliably by means of probes. Moreover, this technique cannot identify potential mavericks caused by surface degradation during subsequent processing. Also it is impossible to apply bias to all devices on the wafer during irradiation.

4. Correlation with Preirradiation Parameters

Arimura et al. (Ref. 3) attempted to find preirradiation electrical parameters that exhibit any correlation with total dose radiation sensitivity. No such correlation could be found with 1/f noise, burn-in changes and the input bias current of an operational amplifier.

III. SCOPE OF MJS'77 IRAN PROGRAM

1. Device Types

IRAN was considered for device types that were determined to be more radiation sensitive than allowable by the circuit and shielding analyses. However, such screening methods work only when the devices show a significantly varied response to a radiation exposure. A list of device types that were considered for IRAN is shown in Table I. The devices consist of linear bipolar devices, analog switches, n-channel JFETs and bipolar transistors. The primary cause of radiation damage induced in these devices by ionizing radiation is the formation of inversion layers due to the accumulation of positive charges in the silicon oxide insulator near the silicon-silicon oxide interface. This depends on the quality of the oxide, which is to a large extent an uncontrolled process variable.

Devices that are generally extremely sensitive to ionizing radiation, e.g., MOS devices, are poor candidates for the IRAN technique and must be shielded. An additional reason for excluding MOS devices is the difficulty of annealing out the radiation induced interface states except at high temperatures. The important LM108 operational amplifier was excluded, because it had been possible to harden this device against ionizing radiation (see Ref. 1).

TABLE I

Device Types Considered for IRAN

Operational Amplifiers	HA2520 HA2600 HA2620 HA2700 LM101
Comparator	LM111
Voltage Regulators	LM105
Analog Switches	DG129 DG133 DG141
JFETs (n-channel)	2N4093 2N4391 2N4392 2N4393 2N4856 2N5196 2N5520 2N5556
Bipolar Transistors h_{FE}	SDT5553

All n-channel JFETs with a lightly doped base region are likely to develop sizeable gate leakage currents and were therefore considered to be candidates for IRAN. It was considered preferable to redesign circuits, so that bipolar transistors could operate with minimum d.c. current gain rather than resort to IRAN. The SDT5553 is a special case and is discussed in detail later.

2. Program Constraints

The original requirement imposed on the devices was to survive a total dose of 125 krad(Si). This was later decreased to 60 krad(Si) as the result of a more precise definition of the Jovian radiation belt.

A ceiling of 150°C was imposed on the annealing temperature of the devices for reliability reasons. It was found that this temperature is inadequate for complete annealing of all surface effects. Burn-in temperatures up to 300°C have been successfully employed in high reliability programs (Ref. 10), but this requires device construction analysis and thermal stress analysis for each device type before procurement. Such an investigation was ruled out because of timing constraints. The devices were annealed in an inert atmosphere for 96 hours. Experiments showed that longer annealing times did not result in any additional annealing.

High temperature annealing was considered to be unnecessary for the JFETs. In these devices only the leakage currents are affected by the ionizing radiation; these are not significant in those devices that pass the IRAN acceptance criteria.

3. Experimental Investigation

The following information is required to determine the suitability of an irradiate-anneal screening program:

a. What is the optimum dose for screening? Too low a dose may not reproduce the surface effects that cause degradation at higher doses, whereas too high a dose degrades the devices unnecessarily. The onset of surface effects caused by inversion layers depends on the impurity concentration in the silicon as well as the composition of the oxide at the silicon interface, and can therefore not be uniquely determined.

b. What acceptance criteria can be applied? Unless there is complete retracking of all devices on reirradiation, the acceptance criteria need considerably more safety margin than the worst case conditions required by the application. On the other hand, conservative specifications may cause yield penalties.

c. What is the annealing behavior? Do all the parameters anneal completely or is there some residual radiation damage? Are there indications of anomalous annealing?

d. Do the parameters retrack on reirradiation or do they exhibit memory effects? Do any of the devices show anomalous properties that could not have been predicted from the results of the first irradiation?

A series of experiments was conducted on each device type under consideration for IRAN. Non-flight parts had previously been exposed to 2.5 MeV electrons up to 10^{13} e/cm^2. These devices were annealed at 150°C for 96 hours approximately two to three months after the initial exposures. Most parameters annealed back to the vendor's specification levels, but did not return to their preirradiation values. Since high energy electrons can induce a significant amount of displacement damage, it was decided to carry out additional experiments using a Cobalt-60 source. The devices were irradiated to a total dose of either 50 or 125 krad(Si), annealed at 150°C for 96 hours and subsequently reirradiated with 2.5 MeV electrons, making electrical parameter measurements at four radiation levels from $5x10^{11}$ to $5x10^{12}$ e/cm^2.

IV. SUMMARY OF RESULTS

1. Linear Bipolar Devices

The effect of irradiate-anneal has been measured for a number of linear bipolar devices, and the results are summarized in Table II, where normal and anomalous values obtained after the first irradiation and annealing are indicated. The parametric changes produced in each device by equal doses of the first and second radiation were plotted so as to indicate the ratio of the shift on reirradiation to the shift after the first irradiation, as well as any anomalous data points. An example is shown in Fig. 1. In almost all cases reirradiation produces substantially greater shifts. No consistent results could be obtained for some combinations of parameters and radiation levels.

TABLE II

IRAN and Reirradiate Parameters of Linear Bipolar Devices

Device Type	Parameter Unit	IRAN Total Dose (krad)	No. of Devices Tested	First Irradiation Values			Anneal Values			Reirrad/1st Irrad Ratio $\Delta R/\Delta I$	Normal Reirradiate Curve Shape*
				Range of Normal Values		Anomalous Values	Range of Normal Values		Anomalous Values		
				Low	High		Low	High			
HA2520	ΔV_{OS} mV	50	6	+ 0.8	+ 1.64		+ 0.25	+ 0.65		1.6	A
		125	6	+ 2.2	+ 1.4	-1.9	+ 0.3	+ 1.4	-0.1	1.0	A
	ΔI_{OS} nA	50	6	-21.4	+ 5.8		+ 2.0	+ 1.8	-2.6	1.55	A
		125	6	-10.2	+ 15.2	-20, -22.5	- 2.2	+ 0.6	+4.8, -7.8	1.0	A
	ΔI_B nA	50	6	+83.	+316.5		+31.	+79.		1.7	A
		125	6	+265.	+446.		+11.9	+74.		1.0	A
	ΔA_{OL} x 1000	50	6	- 5.2	- 10.1		- 4.8	- 6.8		ΔR=0.9 ΔI-3.6K	E
		125	6	- 7.1	- 11.2		- 3.1	- 6.5	-9.8	ΔR=1.23 ΔI+0.84K	E
HA2600	ΔV_{OS} mV	50	6	+ 0.03	+ 0.28		- 0.04	+ 0.04	-0.18		
		125	9	+ 0.02	+ 2.0		- 0.02	+ 0.12	-0.78,+0.965	2.3	
	ΔI_{OS} nA	50	6	+ 0.02	+ 14.4		+ 0.4	+ 3.4	+6.8 to +21.1	2.6	A
		125	9	-22.3	+ 4.0	+32.4,+35.9	- 0.03	- 6.6	+21.1	2.3	
	ΔI_B nA	50	6	+ 3.6	+ 10.1		- 0.5	+ 5.9	+13.7	2.0 to 4.2	A
		125	9	- 0.13	+ 16.5	-4.9,+52.7	- 0.75	+ 0.60	+11.9	1.8	
	ΔA_{OL} x 1000	50	6	-83.	-102.	-1050	-68.	-90.	-95,-1850	1.8	E
		125	9	- 1.4	-101.3	**	-17.4	-7317		1.6	E
HA2620	ΔV_{OS} mV	50	6	+ 0.2	+ 0.7		- 0.06	+ 0.07			A
		150	10	+ 0.06	+ 0.20	-0.34,-1.76 +1.9	- 0.06	+ 0.06		2.3	A
	ΔI_{OS} nA	50	6	- 6.7	+ 2.25		- 0.7	+ 1.15	-12.2,-3.5, +25.4		
		150	10	- 0.05	- 14.4	-27.1,-23.2	- 2.3	+ 3.85		7.	
	ΔI_B nA	50	6	+ 0.44	+ 4.9		+ 0.3	+ 1.5	-2.3	3.	
		150	10	+ 1.0	+ 2.6	-0.4,-0.6, +4.5,+5.9	- 0.5	+ 2.1	+4.0	5.5	A,K
HA2700	ΔV_{OS} mV	50	6	+ 0.14	+ 0.29		+ 0.01	+ 0.12		4.2	A,K
		150	5	+ 0.2	+ 0.36		+ 0.03	+ 0.18	-0.001	2.4	K
	ΔI_{OS} nA	50	6	- 0.6	+ 0.5	+ 1.3	- 0.6	+ 0.80			
		150	5	- 0.14	- 0.70	+ 1.48	- 0.1	+ 0.9	-1.0	5.	A
	ΔI_B nA	150	5	- 1.6	- 4.7		- 4.2	- 5.1		1.9	A,N
LM101	ΔV_{OS} mV	50	6	- 0.1	- 0.6		- 0.3	+ 0.06			K
		125	11	- 0.16	+ 0.8		- 0.26	+ 0.16		9.	K
	ΔI_{OS} nA	50	6	- 1.6	+ 1.2	+5.0	- 0.02	- 0.4	+0.6		A,K
		125	11	- 2.7	+ 1.6	-4.1	- 0.7	+ 2.2		2.5	K
	ΔI_B nA	50	6	-10.5	- 14.9	+2.5,-3.5	- 0.6	+11.8		-4.3	
		125	11	+25.	+ 50.		+ 0.5	+56.		2.5	K
LM105	ΔV mA Load and Line Reg.	50	6	-12.	+ 6.4		not measured			1.35	Z,H
		100	4	- 3.	11.	-75	not measured				
LM111	ΔV_{OS} mA	50	16	+ 0.4	+ 1.5		- 0.28	+ 0.76		2.1	A
		125	6	+ 1.5	+ 3.0		- 0.07	- 0.38		1.5,2.1	K
	ΔI_{OS} nA	50	16	-17.3	- 1.1		-21.6	+20.6		2.2	A
		125	6	-12.5	- 74.3	+36.8	-31.	+20.	+217	1.8,3.3	A
	ΔI_B nA	50	16	+193.	+442.		+357.	+841.			Q
		125	6	+350.	+1107.		+728.	+968		1.4	V

* see Figure 5.
**4 devices failed A_{OL} test after first irradiation.

LEGEND: ΔV_{OS} = change in offset voltage
ΔI_{OS} = change in offset current
Δ_{IS} = change in input bias current

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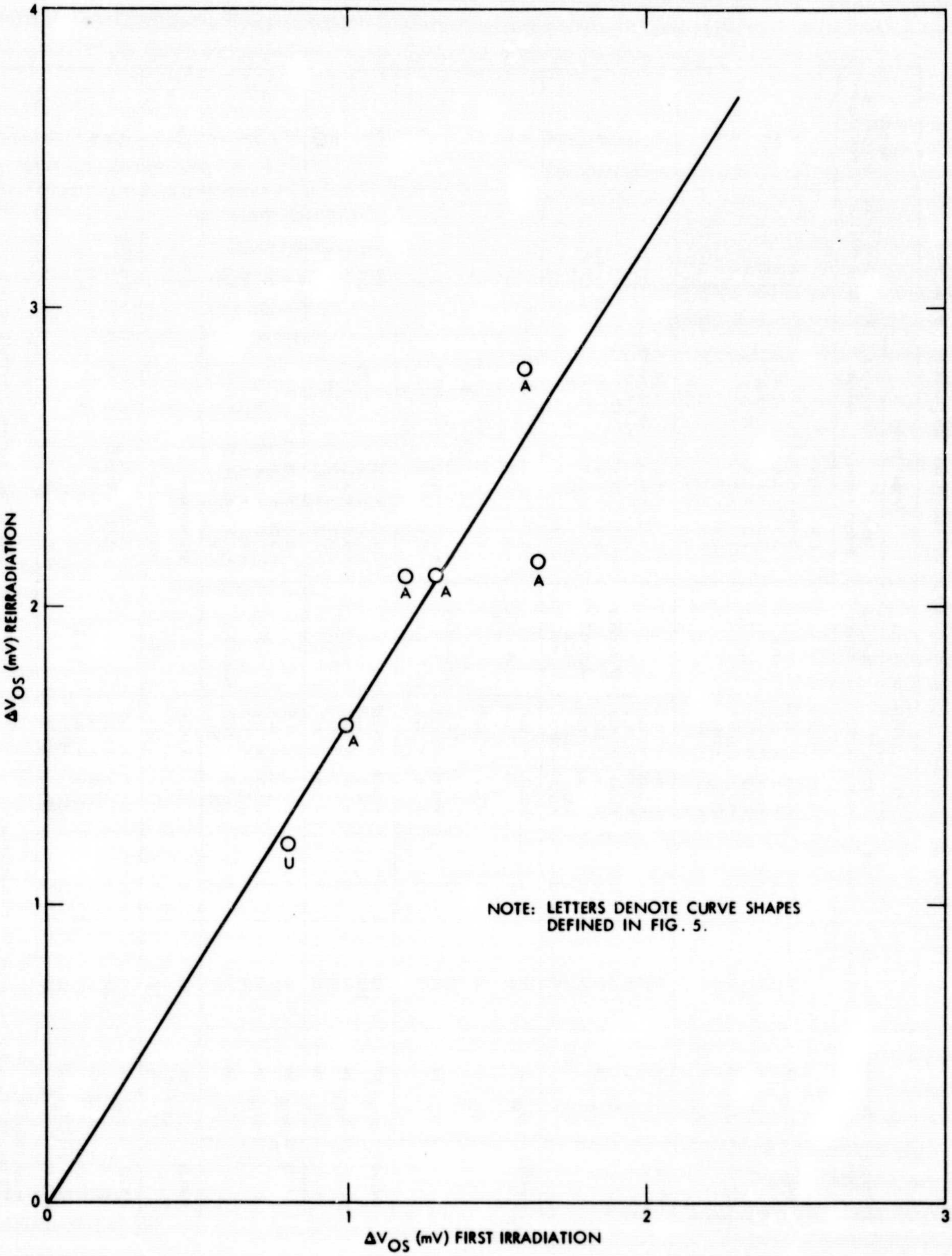

Fig. 1. Irradiate Versus Reirradiate at 50 krad(Si) for ΔV_{OS}; HA2520

On annealing most parameters recover to within the manufacturer's specification limits. However, the open loop gain never recovers and this also applies to the input bias current of the HA2520. In this paper the changes in parametric values have been calculated with reference to the original preirradiation value. Since the open loop gain of HA2520 does not anneal the reirradiate/first irradiation ratio becomes a linear function that does not go through the origin. (See Table II.)

The LM111 exhibited some unusual annealing phenomena. The input offset current (I_{OS}) produced a negative shift during the first irradiation a 50 krad(Si). On annealing, this parameter shifted in the positive direction overshooting its original value by as much as 15 nA. The input bias current (I_B) increased to about 400 nA during the first irradiation. Annealing produced further deterioration in this parameter by up to an additional 400 nA.

a. Reirradiation Curve Shape

During the initial irradiation most linear bipolar devices exhibit slow parametric changes up to about 35 krad(Si) followed by a logarithmic variation with total dose (Φ) of the type (see Fig. 2):

$$P = k\log\Phi + \text{constant}$$

After irradiation to 50 krad and annealing there is a slow parametric change up to 10 krad (Si) or reirradiation followed by a logarithmic response of the type (Fig. 3):

$$P = k\log(\Phi - \Phi_C) = \text{constant}$$

where Φ_C is the difference in total dose producing equal parameter changes after the first irradiation and after reirradiation. Φ_C lies between 30 and 40 krad(Si), i.e., on reirradiation the damage is more severe due to a memory effect.

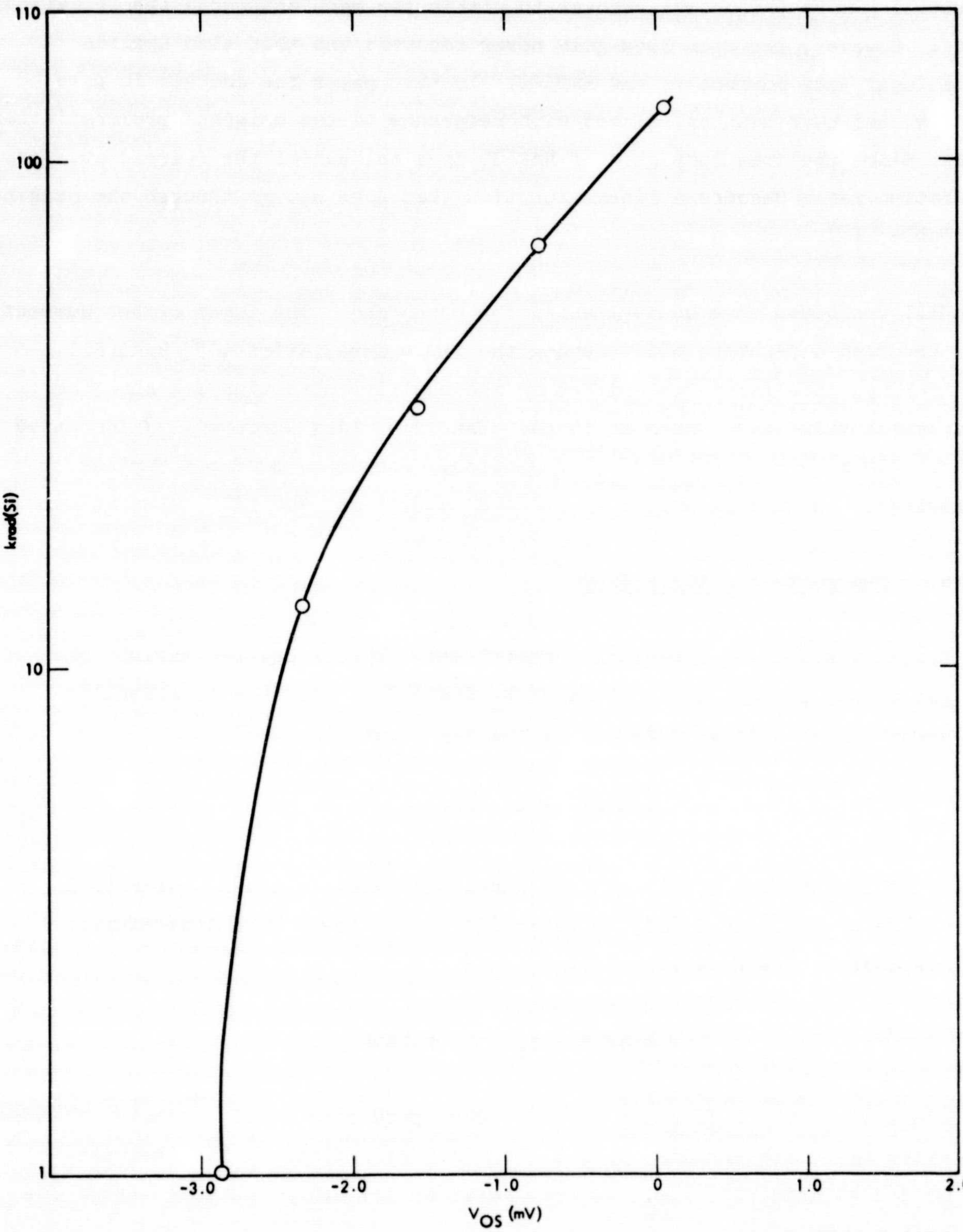

Fig. 2. Irradiation Response Curve of V_{OS}; HA2520

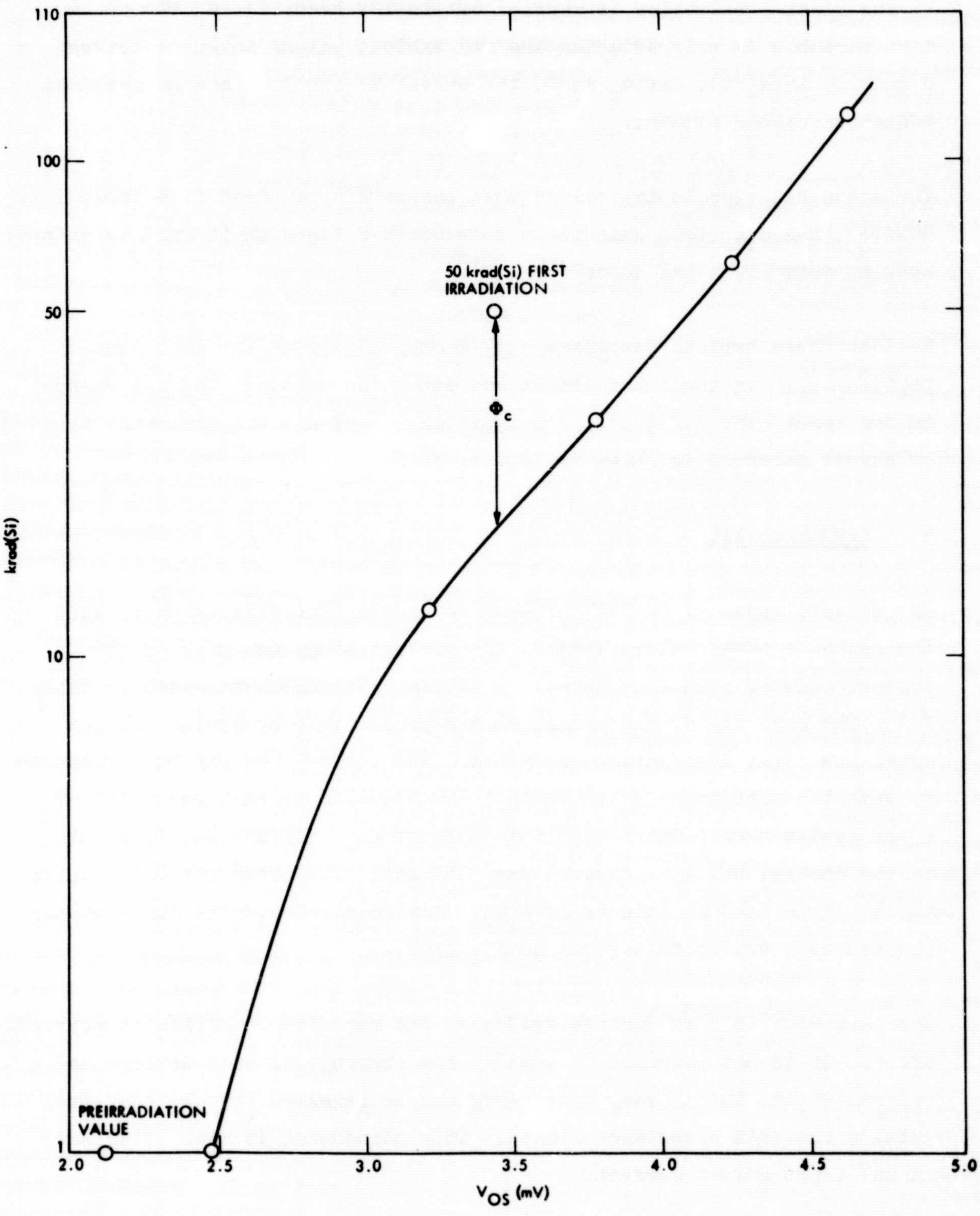

Fig. 3. Reirradiate Curve of V_{OS}; HA2520

If the first irradiation is carried out to 125 krad(Si), Φ_C becomes much more variable on reirradiation and may exhibit values anywhere between 0 and 100 krad(Si). If Φ_C is 0, the anneal is complete and no residual radiation damage remains.

The above behavior is typical of most parameters measured (see Table II). However, the open loop gain tends to exhibit a logarithmic dose dependence even at very low total doses (Fig. 4).

Besides these typical responses many anomalous curves are also seen, particularly for the input offset current which measures the difference in two input bias currents. A classification of all the different types of curves observed is shown in Fig. 5.

b. Predictability

The effectiveness of an IRAN program depends on the ability to predict the response under reirradiation. A thorough study was made of the factors causing anomalous behavior. The results are summarized in Table III. The majority of the anomalies are predictable by deviant values after the first irradiation and anneal, and the devices may be eliminated by suitable acceptance criteria that are specific to each parameter of every device type. These take into account not only the absolute value of the change, but also unusual sign changes. The unpredictable results may be classified as changes in sign, anomalous reirradiate curve shapes and causes specific to a given device type.

The parameter in some devices drifts in the opposite direction on reirradiation. It is not possible to predict the response of such devices on reirradiation, but in many cases they may be rejected because they fall outside the IRAN acceptance limits. This phenomenon is most often seen in the input offset current.

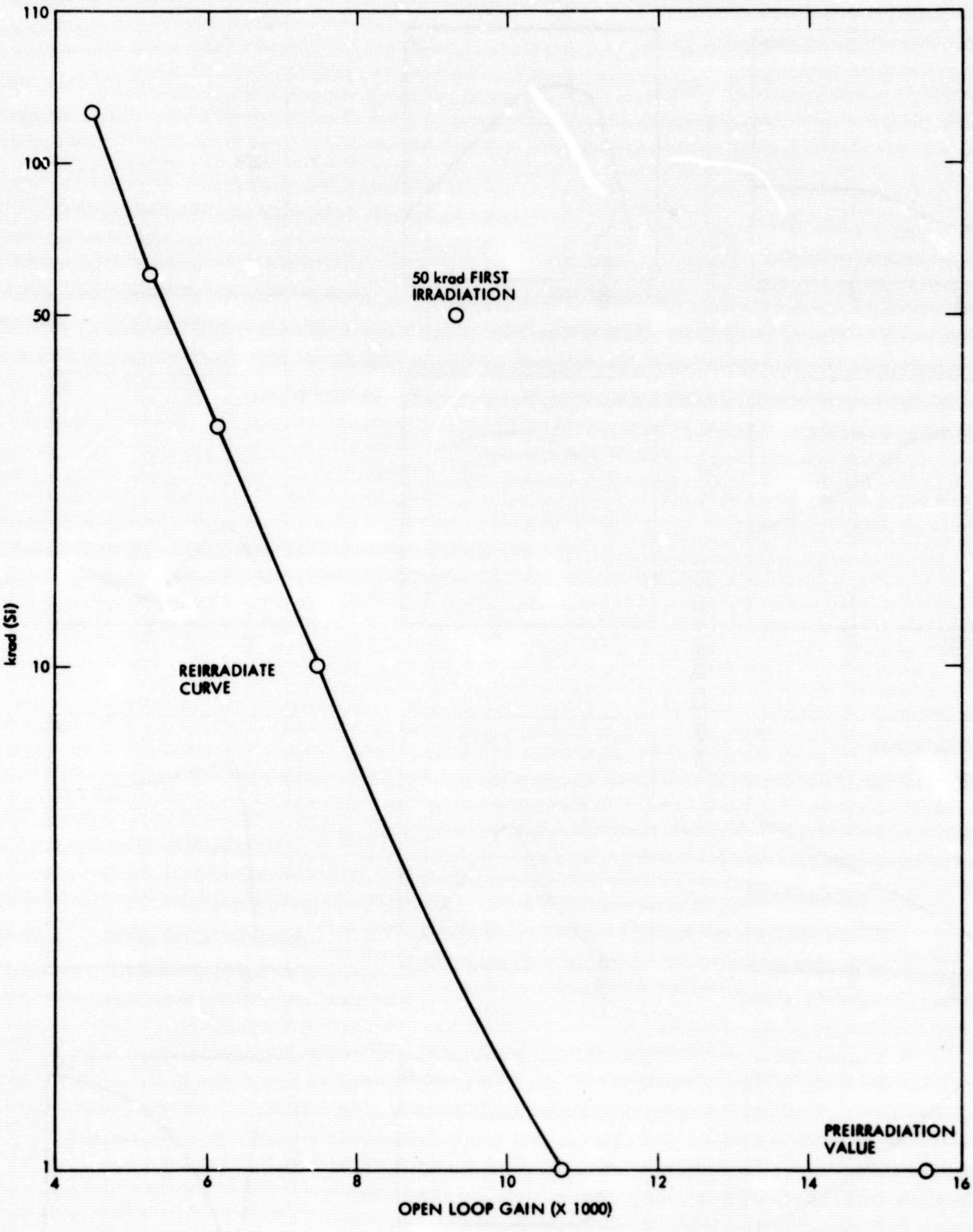

Fig. 4. Reirradiate Curve for Open Loop Gain; HA2520

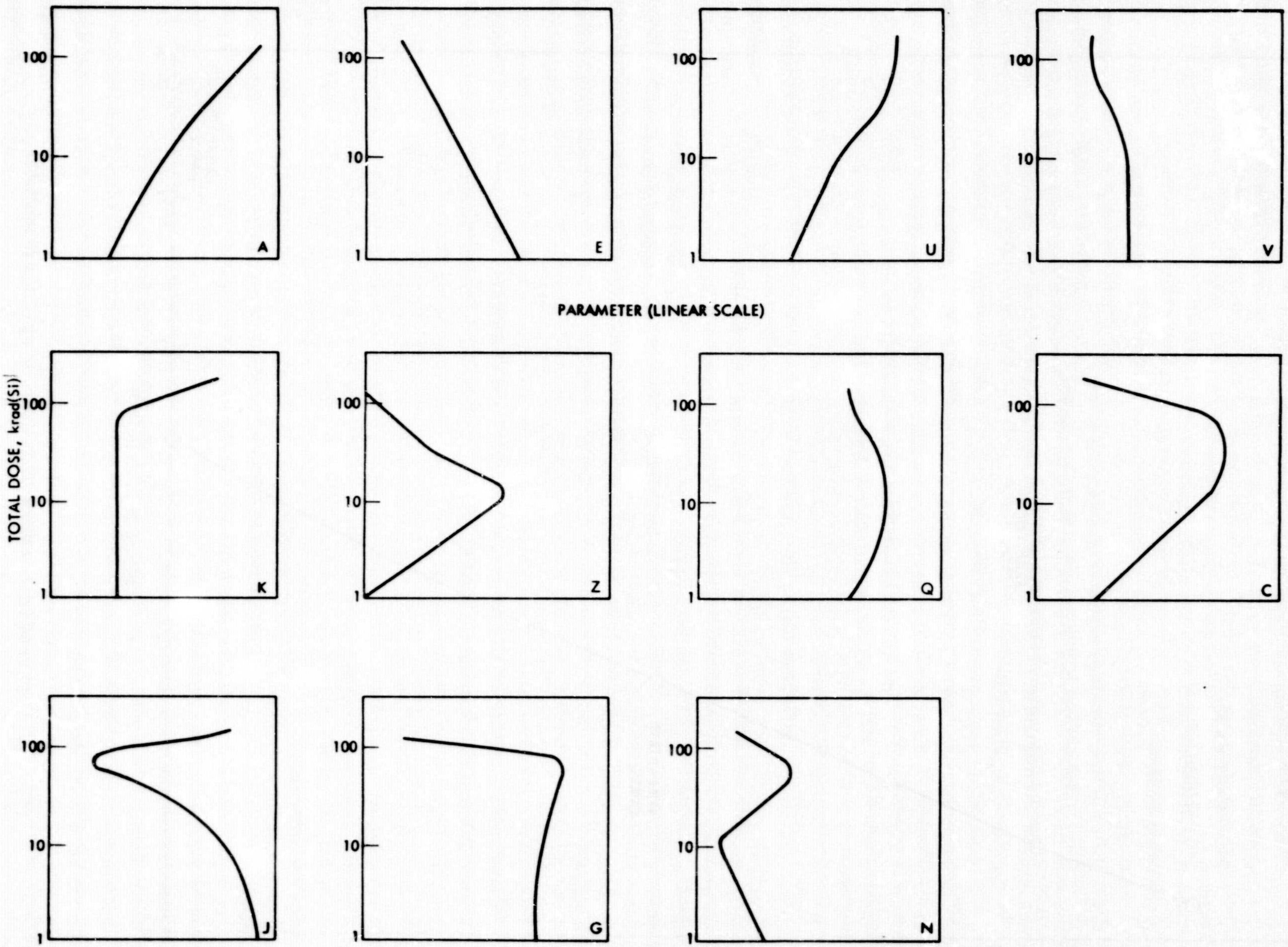

Fig. 5. Reirradiate Curve Shapes of Linear Bipolar Devices

TABLE III

Classification of Anomalous Reirradiate Curves

Device Type	Parameter	IRAN Total Dose(krad)	Predictable Anomalies		Sign Change	Unpredictable Anomalies Anomalous Reirrad. Curve Shape*			Other
			IRAN	Anneal		Same	Better	Worse	
HA2520	ΔV_{OS}	50	1	1		U			
		125		1			C		See text
	ΔI_{OS}	50		1		J			
		125							See text
	ΔI_B	50							
		125							All, see text
	ΔA_{OL}	50							
		125		1					See text
HA2600	ΔV_{OS}	50		1			Q		All, see text
		125							
	ΔI_{OS}	50		4					
		125			1				
	ΔI_B	50				Q,Z			
		125	2	1		N,Z			
	ΔA_{OL}	50		1				K	
		125				A,V			
HA2620	ΔV_{OS}	50				G	U		All, see text
		150	3			U			
	ΔI_{OS}	50		3					
		150	2		3	N,U	J		
	ΔI_V	50		1	1	A,J	K		
		150	5	1					
HA2700	ΔV_{OS}	50		1					
		150		1					
	ΔI_{OS}	50	1		1	U	N,Z		
		150	1	1		N			
	ΔI_B	150							
LM101	ΔV_{OS}	50			All				All, see text
		125					Q,G		
	ΔI_{OS}	50	1	1					See text
		125	1			G,N			
	ΔI_B	50	2		All				See text
		125				Z			
LM105	Load & Line Reg.	50							
		100	1		2	Z			See text
LM111	ΔV_{OS}	50	1		2	K			
		125				A			
	ΔI_{OS}	50	1		2		Z		
		125	1	1		U			
	ΔI_B	50	1			Z			
		125				C	N		

*see Figure 5.

The other principal cause of non-predictability is the anomalous shape of the reirradiation curve. However, many anomalous curve shapes produce reirradiate values that are either the same or better than those produced by the standard curve. Worse values occur if the shape of the anomalous curve becomes logarithmic only beyond 60 krad(Si).

The behavior of the input offset current is most unpredictable. Both positive and negative shifts are common. In the course of reirradiation the absolute value of this parameter may go through one or two maxima at intermediate dose levels. However, it is possible to define a maximum shift in either direction that this parameter is not likely to exceed. Anomalous results in specific device types will now be considered. Highly irregular reirradiation values were obtained in all parameters of the HA2520 when the total dose of the first irradiation was increased to 125 krad(Si). This treatment caused some devices to improve on reirradiation while in others Φ_C was displaced by up to 100 krad(Si). This resulted in poor correlation of the reirradiate values. The mean reirradiate/first irradiation ratio is unity for all d.c. parameters in this device only. No trends could be established in the reirradiation pattern of the input offset voltage of the HA2600 and HA2620, when the first irradiation was carried out at a total dose of 50 krad(Si). In the case of the HA2620 the parameter shift during the first irradiation was very small, whereas a very large nonlinear shift was seen at higher doses on reirradiation. These uncertainties could be resolved by increasing the first irradiation dose to 150 krad(Si) (see Fig. 6).

All the LM101 devices irradiated at 50 krad(Si) behaved anomalously. The parameters shifted in the opposite direction on reirradiation, and some devices exhibited large increases at total doses above 60 krad(Si). It was, therefore, decided to carry out IRAN at 125 krad(Si) on this device type, since more consistent results could thus be achieved. On the other hand, no reproducible shifts in the output voltage of the LM105 voltage regulator could be obtained on reirradiation after the devices had been subjected to IRAN at 100 krad(Si).

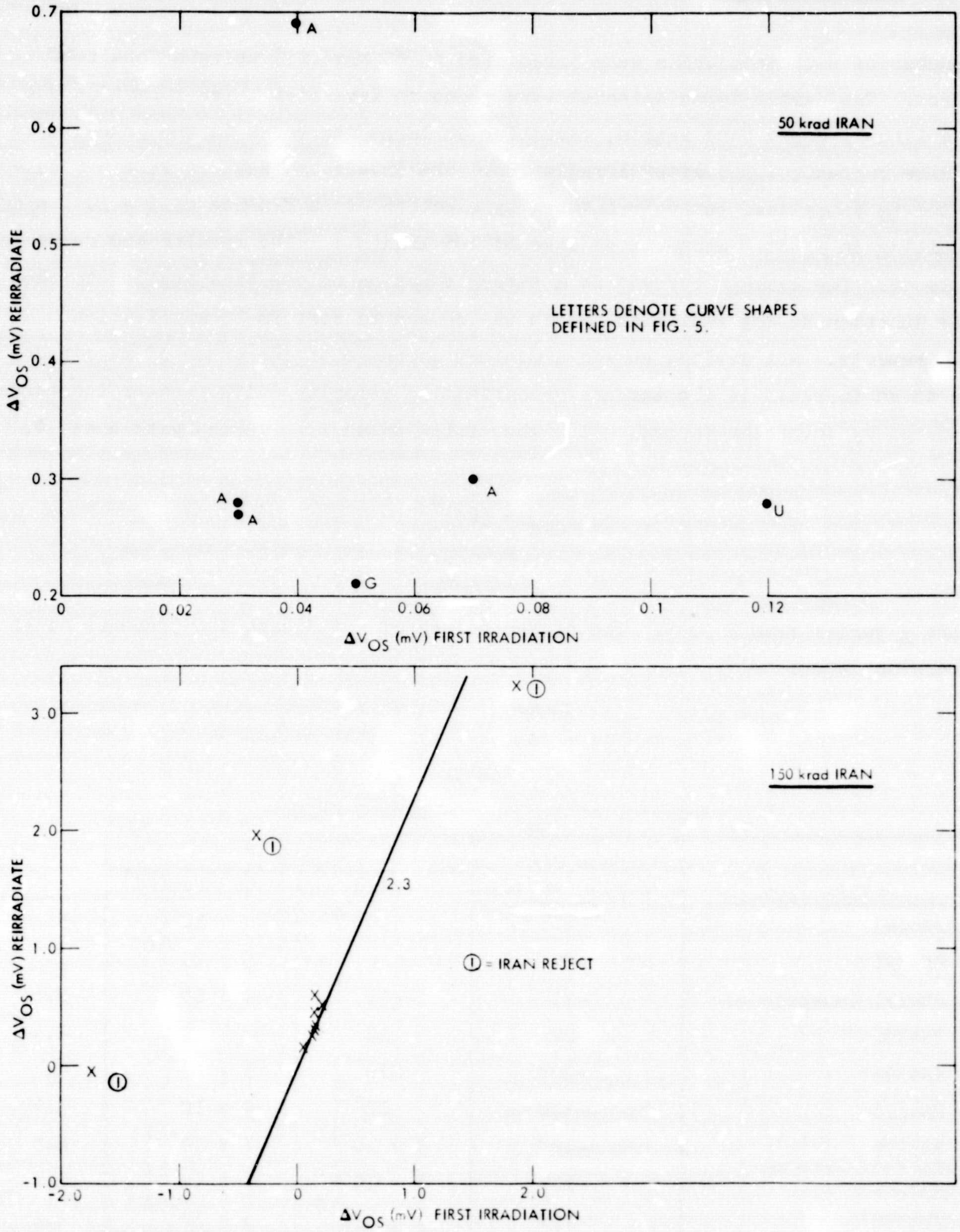

Fig. 6. Irradiate Versus Reirradiate for ΔV_{OS}; HA2620

2. N-Channel JFETs

A number of n-channel JFETs were irradiated to 60 krad(Si) using a Cobalt-60 source. The device types selected were prone to inversion layer formation due to a lightly doped base region, resulting in large increases in the gate-source leakage current, I_{GSS}, after irradiation. The irradiated devices were not subjected to annealing, but reirradiated by electrons to a fluence of 5×10^{12} e/cm^2 resulting in a total accumulated dose of 185 krad(Si). The results are shown in Table IV. The leakage current is a strong function of the bias applied to the gate junction during radiation, which was chosen to conform to applications requirements. All devices showed a minimum increase of one order of magnitude due to an increase in the surface recombination velocity, with greater increases produced by inversion layers. At higher total doses I_{GSS} varies with dose, Φ, as:

$$I_{GSS} = (k\Phi)^a$$

where a varies from 2 to 5. The higher values of a indicate the presence of an inversion layer.

TABLE IV

Behavior of I_{GSS} of N-Channel JFETs

Device Type	Gate Bias During Irrad.	I_{GSS} (A) Prerad.	I_{GSS} (A) 60 krad(Si)	a
2N4093	-20V	10^{-10}	10^{-9}	5
2N4391	-20V	10^{-10}	3×10^{-10}	2
2N4391 (unscreened)	-20V	10^{-10}	9×10^{-10}	2.4
2N4392	-20V	10^{-10}	10^{-9}	2.4
2N4393	-20V	10^{-10}	5×10^{-9}	4
2N4856	-20V	10^{-11}	4×10^{-10}	3.4
2N5196	-10V	5×10^{-11}	7×10^{-11}	2.5
2N5520	-10V	5×10^{-11}	7×10^{-11}	2.2
2N5556	-15V	10^{-10}	3×10^{-10}	2.2

3. Analog Switches

Three types of analog switches were irradiated at 50 or 100 krad (Si) followed by 96 hour annealing at 150°C and reirradiation. During irradiation the positive and negative supply voltages were kept at +12 and -18V respectively and the input voltage at +4V. The latter corresponds to the on-state which had previously been identified as worst case condition. The n-channel JFETs in the devices can cause an increase in I_S (off), the most sensitive parameter in those devices not containing MOS components. The MOS devices are extremely radiation sensitive and were not considered suitable for irradiate-anneal procedures.

Typical values are shown in Table V. On reirradiation I_S (off) obeys the relationship:

$$I_S = (k\Phi)^a$$

over the dose range between 30 and 125 krad(Si). No serious radiation induced inversion layers were seen in these devices, resulting in a values between 1.4 and 2. The residual radiation effects shown in the Table indicate that after irradiation, anneal and reirradiation I_S (off) appears to have been subjected to additional radiation equivalent to 20 or 50 krad(Si) depending on the total dose during the first irradiation.

4. Bipolar Transistors

The only bipolar transistor subjected to IRAN procedures in the MJS program is the SDT 5553, a device extremely sensitive to surface ionization effects at low current levels. This device was used only in a shielded environment (less than 5×10^{11} e/cm^2 fluence) at a collector current of 150 μA and a collector emitter voltage of 124V.

The devices were irradiated to a total dose of 5 krad(Si), and all devices with d.c. gain of less than 8 were rejected. $\Delta(1/h_{FE})$ varied by more than 3 orders of magnitude (see Table VI). The devices were then annealed at 150°C for 96 hours.

TABLE V

Typical Values for Analog Switches

Total Dose Levels (krad (Si))		Parameter	DG129, DG133	DG141
1st Irradiation	Reirradiation			
First Irradiation				
50		I_S (off)	300 pA	500 pA
100		I_S (off)	1 nA	2.5 nA
Reirradiation				
50,100	30	I_S (off)	300 pA	700 pA
50	30 to 125	a	2	2
100	30 to 125	a	1.4	1.4
Residual Effects Produced by IRAN				
50	50	Ratio of I_S (off)	2.4	2.25
100	100	Ratio of I_S (off)	2.4	1.6
50		Φ_C = Residual Radiation Effect After IRAN	20 krad	20 krad
100			50 krad	50 krad

Some devices were reirradiated to a total dose of 25 krad(Si). The reirradiate/first irradiation ratio varied from 1 to 5.6 and the residual radiation damage varied from 1 to 4.5 krad(Si). Above 5 krad(Si) there was a sharp increase in $\Delta(1/h_{FE})$ due to the onset of a response of the type

$$\Delta(1/h_{FE}) = (k\Phi)^a$$

a decreased with initial radiation damage and was lowest for devices with the worst radiation damage (see Table VI).

A few devices were subjected to irradiate-anneal at 25 to 60 krad(Si). On reirradiation to a total dose of 12.5 krad(Si), these devices exhibited a less rapid total dose response and a more predictable reirradiation behavior at the expense of introducing greater radiation damage. The SDT 5553 showed no annealing anomalies, but the anneal was always incomplete.

TABLE VI

$\Delta(1/h_{FE})$ of SDT 5553

IRAN AT 5 krad (Si)

Device No.	$\Delta(1/h_{FE})$ at 5 krad (Si): 1st Irradiation	$\Delta(1/h_{FE})$ at 5 krad (Si): Reirradiation	Ratio	Reirradiation Characteristics: Onset of Power Law Response: Dose (krad)	Onset of Power Law Response: $\Delta(1/h_{FE})$	Onset of Power Law Response: a	Displacement of Reirradiate Curve (krad)	Anneal Shift in $\Delta(1/h_{FE})$
1	3.3×10^{-4}	1.24×10^{-3}	3.6	12.5	2.6×10^{-3}	1.45	4.5	2.6×10^{-4}
2	4×10^{-3}	8.5×10^{-3}	2.1	6	1×10^{-2}	1.9	3	1.5×10^{-3}
3	4×10^{-3}	2.25×10^{-2}	5.6	< 2.5	7×10^{-3}	1.4	3	2×10^{-3}
4	9.9×10^{-3}	1.1×10^{-2}	1.1	12.5	1.5×10^{-2}	1.0	1.2	3.85×10^{-3}
5	1.13	1.6	1.4	< 2.5	8.7×10^{-1}	0.8	1.5	1.2×10^{-2}

IRAN AT HIGHER TOTAL DOSE

Device No.	1st Irradiation: Total Dose (krad)	1st Irradiation: $\Delta(1/h_{FE})$	1st Irradiation: a	Reirradiation Onset of Power Law Response: Dose (krad)	Reirradiation Onset of Power Law Response: $\Delta(1/h_{FE})$	Reirradiation Onset of Power Law Response: a	$\Delta(1/h_{FE})$ @ 12.5 krad	Anneal Shift in $\Delta(1/h_{FE})$
6	25	9×10^{-3}	0.7	6	7×10^{-3}	0.6	0.01	4×10^{-3}
7	60	8.5×10^{-2}	1.3	2.5	3.2×10^{-2}	0.4	0.055	2×10^{-2}

An analysis was carried out on IRAN data taken by M. Acuña of Goddard Space Flight Center (Ref. 11) on the d.c. current gain of the 2N2484 transistor at collector current levels of 100 μA, 500 μA and 5 mA. The devices were irradiated at a total dose of 150 krad(Si) and annealed for 96 hours at 150°C. The rejection criterion was a change in $1/h_{FE}$ greater than 1×10^{-3}. The devices were then reirradiated to 150 krad(Si) and annealed a second time.

The reirradiation/first irradiation ratio for acceptable devices varied from 1.5 to 2.5. The ratio was 0.8 for a rejected device and 0.14 for a device showing anomalous annealing, i.e., an improvement in h_{FE} over the original value. Acceptable devices showed incomplete annealing resulting in an increase of 1 to 6×10^{-3} in $\Delta(1/h_{FE})$. The increase was greater at lower current levels.

V. IRRADIATE-ANNEAL OF FLIGHT PARTS

Based on the data described in Section IV, a program to IRAN MJS'77 flight parts was initiated on a number of integrated circuit types, on one bipolar transistor, and on several JFETs. The device types tested are listed in Table VII along with the acceptance criteria and the radiation screening levels developed in the experimental program.

The basic procedure was the same as developed in the experimental program and was carried out as follows; parts were:

1. measured before radiation exposure
2. exposed to one level of radiation dose
3. measured again immediately following radiation exposure
4. annealed at 150°C for 96 hours
5. remeasured at part manufacturer's facility

For JFETs steps 4 and 5 were eliminated.

A detailed test procedure was written to describe the steps required for parts handling, data recording, electrical bias during irradiation, pre- and post-electrical measurements, radiation dose, dose rate and post-irradiation annealing for each device type to be given the IRAN treatment.

TABLE VII
Flight Parts for IRAN Program

Part Types	Number Tested	Number of Rejects	Acceptance Criteria	Screening Dose krad(Si)
LM101A (can)	139	20	$\Delta V_{OS} < 0.7$ mV $\Delta I_{OS} < 2.5$ nA $\Delta I_B < 60$ nA	125
LM101A (flat pack)	396	83		
LM111 (can)	48	0	$V_{OS} < 3$ mV $I_{OS} < 20$ nA $I_B < 1 \mu A$	50
LM111 (flat pack)	200	14		
DG129*	18	0	I_S (off) < 3 nA	50
DG133*	41	0	I_S (off) < 3 nA	50
DG141*	9	0	I_S (off) < 5 nA	50
2N4856	222	65	$I_{GSS} < 500$ pA	60
2N5196	124	17	$I_{GSS} < 100$ pA	60
2N5520	21	0	$I_{GSS} < 100$ pA	60
2N5556	96	28	$I_{GSS} < 250$ pA	60
SDT5553	39	4	$h_{FE} > 8$	5

*Lot Sample IRAN only.

The work was contracted at the Hughes Aircraft Company using their 50 kilocurie Cobalt-60 source located in Fullerton, California. This is a full panoramic source, Gammabeam, Model 650, made by Atomic Energy of Canada Ltd.

A semi-automatic test system was built to test parts _in situ_ for the IRAN screening work. Features of the system include the following:

1. Twenty-four devices could be tested in series along with one control device, which was tested both before and after each series of measurements.

2. The test system was composed of test boards (with socket adaptors for each package type), stepper switches, a Faraday cage, 25 foot long cables (with good radiation resistant insulation and non-coaxial wire), test console, logic system, fixed voltage power supplies, a quality ranging digital volt meter, a digital ammeter, a paper tape recorder, a cassette tape recorder and a computer terminal with an acoustic coupler for telephone connection to a computer.
3. The electrical leakage of the system was reduced to 100 pA or below to allow acceptable accuracy in making device leakage current measurements.

Parts of the system were unique for each device type tested. These were designed and constructed and kept on the shelf just for testing one part type. Such parts included the adaptors, the stepper switches and the test boards. Some minor capability overlap allowed testing more than one device type on some boards. The test method required that all measurements be completed within 15 minutes after the radiation exposure in order to minimize annealing of the radiation induced parameter changes. To accomplish this, the system was designed to automatically step through up to four dc voltage measurements on each device, pausing long enough to achieve equilibrium, and continue through the four measurements for 26 devices in sequence.

The test boards during test were in a flat array at a distance from the Cobalt 60 source which allowed a radiation dose uniformity over the test devices of $\pm 10\%$. The test devices, being flight parts, were handled by defined Quality Assurance (QA) procedures with QA personnel in attendance during each step of the test procedure. The written test procedure defined the QA handling requirements.

After the radiation exposure the devices were removed from the test boards for annealing, were put into a bake tray and placed into a well-regulated inert gas oven for a minimum of 96 hours at $150^{\circ} \pm 2^{\circ}C$. Subsequently, the devices were repackaged in the original containers, returned to JPL and shipped back to the original device manufacturer for repeat measurments of certain key electrical parameters. Reject devices were again designated and the whole lot was then shipped back to JPL for issue to MJS'77 subsystems.

A block diagram of the IRAN procedure is given in Figure 7. A traveler was prepared for each separate group of parts tested with QA sign-off of key steps in the procedure to assure proper conformance.

The total number of each part type subjected to IRAN is given in Table VII along with the number of rejects. It may be seen that about 1/3 of the devices failed the criteria shown in the Table for some part types while others had no failures.

As an additional safeguard some devices for each lot were subjected to reirradiation using a series of four exposure levels from 15 up to 125 krad(Si). This was to insure that the reirradiation electrical parameter values did not exceed the limits that had been used to set the acceptance criteria listed in Table VII, assuming a correlation between the values on the 1st and 2nd irradiation (see Section IV). These limits were well within the requirements of the worst case application of MJS subsystems.

For those parts which had to be annealed, an additional requirement was that the electrical parameters of the flight parts after anneal should return to within the manufacturer's specification limits. However, the input bias current (IB) of the LM101 did not anneal, and IB for the LM111 deteriorated further. The following specifications for IRAN flight parts were adopted:

	Manufacturer's Limit	Post-Anneal Limit
LM101	75 nA	100 nA
LM111	100 nA	1000 nA

VI. CONCLUSIONS

In order to have a successful IRAN screening program it is important that no device on reirradiation fall above certain parametric limits required by the worst case application. This can only be achieved if the following conditions are obeyed:

1. Careful choice of radiation dose and parameter change acceptance criteria.
2. Absence of anomalous anneal phenomena.
3. Absence of anomalous reirradiation effects.

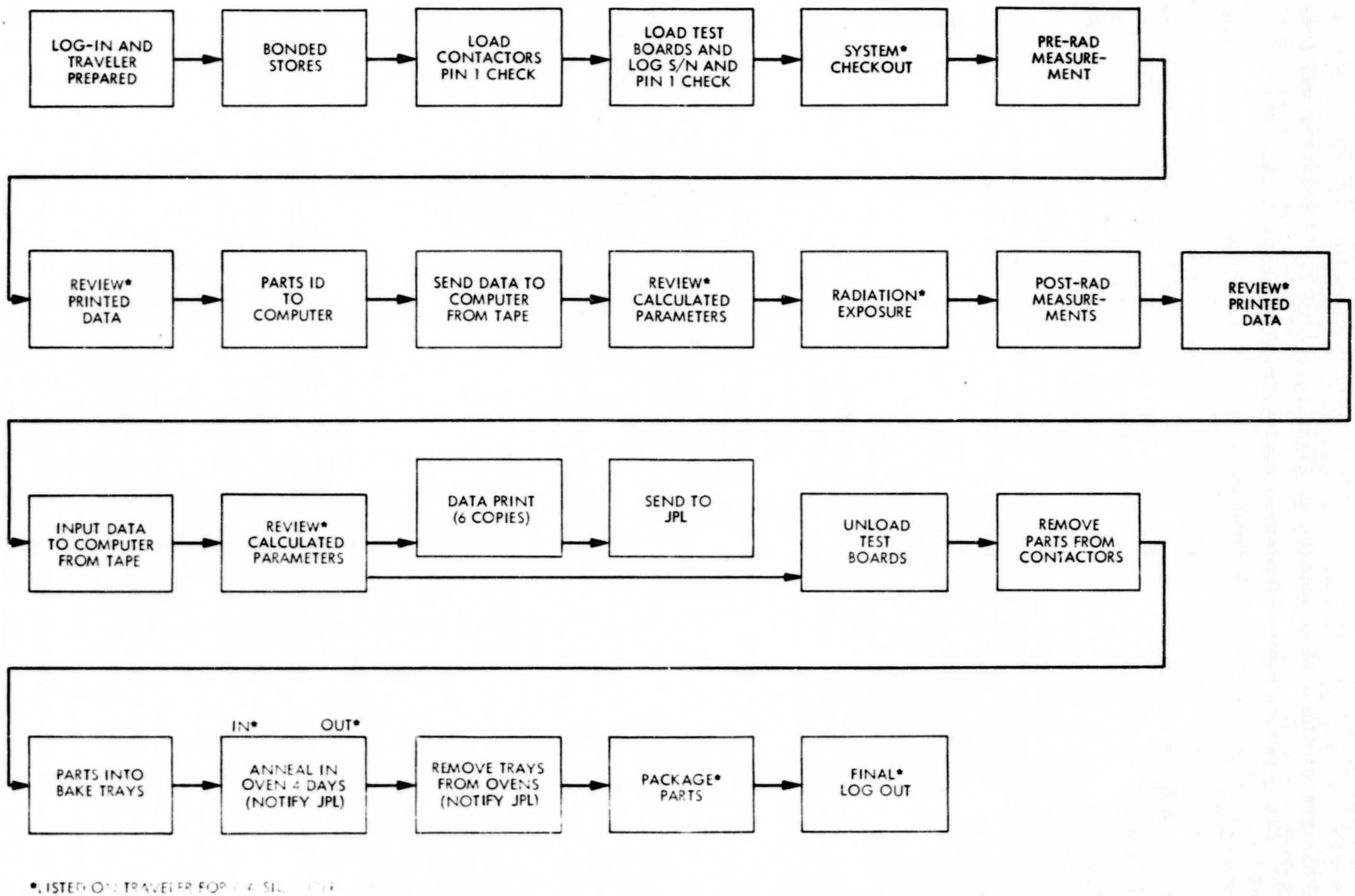

Fig. 7. IRAN Screening Program Procedure

In general, an annealing temperature of 150°C leaves some residual radiation damage and does not guarantee the absence of annealing and reirradiation anomalies. The success of the limited Irradiate-Anneal program on MJS'77 flight parts was due to a combination of the following factors:

1. Non-retracking problem minimized by careful selection of device types to be subjected to IRAN.
2. Remeasuring of devices after anneal by device manufacturer.
3. Reirradiation of sample flight parts to 125 krad(Si).
4. For each critical circuit, analysis determined a permissible worst case parameter value. Reirradiate data indicated that this value would not be approached under the most unfavorable conditions defined as mean plus 3 times standard deviation.
5. Some significant device degradation, e.g., I_B of LM101 and LM111, was tolerated by the circuit designs.

The following device types were found not suitable for IRAN for reasons given:

1. HA2520, HA2600, HA2620; no correlation was found between IRAN and reirradiation behavior.
2. HA9-2700 (flat packs); severe degradation occurred in negative open loop gain during the first irradiation from which the devices did not recover on annealing.
3. JFETs: 2N4093, 2N4393, 2N5906. The flight lots were found to be extremely radiation sensitive requiring shielding; i.e., no screening is possible if all devices are bad.

Other devices which were investigated for IRAN but not included in the flight device IRAN program were as follows:

1. HA2-2700 (cans), 2N4391, 2N4392; lot sample testing was found satisfactory for these.
2. LM105 (voltage regulator); radiation damage for all devices was found to be acceptable up to 60 krad(Si).

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